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LIMITED CIRCULATION

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AGRICULTURAL MEMORANDUM NO. 1010

The Feasibility of Barn Drying Hay in the United Kingdom

by M J Lee

1. Introduction

Jeppsson (1979) describes the way in which a large amount of Scandinavian hay is dried. The process involves picking up the hay whilst it still has a high moisture content (up to 50% of the weight on a wet basis). The moisture content is then reduced to about 20% by spreading the hay on a raised floor in a barn, and blowing ambient air through from below.

In the UK summers are characteristically warm but more humid than those experienced on the continent, which would make barn drying of hay more difficult and inefficient. Humidity regimes at various British localities has been investigated in a similar way to that used by Jeppsson (1979), to see whether barn drying is a viable proposition. The results are reported in this memorandum.

The work of Jeppsson is not quite meteorologically rigorous, as will be explained later, which makes comparison between the UK and Sweden not as easy as it could be.

2. Theory

The degree to which hay will dry, or indeed whether it will dry at all, depends upon the relative humidity of the air in contact with it. There are maximum humidities acceptable for drying hay to particular moisture contents. These equilibrium humidities are shown by the upper curve of Figure 1. Figure 1 also shows a moisture absorption curve, but the work of others (for example Shepherd (1957)) indicates that it may be wrong, there should be less strong hysteresis.

The quantity of moisture in the air is usually expressed as a vapour pressure or mixing ratio, but Jeppsson chose to use a vapour density (grams of vapour per cubic metre of air) to express the moisture content. The ability of the air to absorb more moisture can be expressed as a vapour density deficit (henceforth VDD), being the difference between the vapour density of saturated air and the actual vapour density of the air.

In barn drying the thermodynamic processes taking place are adiabatic, that is they occur at constant pressure with virtually no external heat sources. Consequently as the hay moisture evaporates the latent heat has to be extracted primarily from the air. The air

temperature will fall until the evaporation stops when the air becomes saturated. When saturated the air will be in equilibrium with and hence have the temperature of the wet-bulb, or in this case that of the hay stalks.

The wet-bulb temperature is not a constant, radiation from the warmer surroundings and conduction through the evaporating surface will tend to raise the wet-bulb temperature. The amount of conducted heat is dependent upon the size, shape and type of evaporating surface. The wet-bulb temperature will be raised still further if the air flow is not strong enough to remove air immediately in contact with the evaporating surface before it approaches saturation, which impedes evaporation. The slower the air flow, the great the restriction on evaporation, resulting in the need for less latent heat, and increasing the wet bulb temperature at which saturation occurs. In fast air flows, the only restriction on evaporation is caused by the moisture content of the ambient air, and in conditions where radiative and conductive heating are negligible the wet-bulb temperature tends towards an ideal value, the thermodynamic wet-bulb temperature. This temperature is closely approximated by a Psychrometer.

To calculate vapour pressure the following equation can be used:

$$e = e_{sw} - Ap\ (T - T_w) \qquad (1)$$

where e = vapour pressure (mb)
e_{sw} = saturation vapour pressure at the wet bulb temperature (mb)
P = atmospheric pressure (mb)
A = Psychrometric 'constant' ($^{\circ}C^{-1}$)
T = air temperature ($^{\circ}C$)
T_w = wet bulb temperature ($^{\circ}C$).

In order to obtain the correct value of e from the variable values of T_w and e_{sw} (which is a function of T_w), the value of the Psychrometric Constant (A) has to be correctly selected. In ideal conditions

$$A = c_p M_d / L_v M_v = 6.59 \times 10^{-4}\ ^{\circ}C^{-1} \qquad (2)$$

where c_p = specific heat of air at constant pressure
L_v = latent heat of vapourisation
M_d = molecular weight of dry air
M_v = molecular weight of water vapour

In non-ideal conditions A has to be empirically calculated for each temperature measuring device. For a Stephenson screen A is set to 7.89×10^{-4}. Experimental work has shown that A can be double the ideal value in slow air movement (a few centimetres per second) for a large thermometer. For hay stalks in a barn having air passed through them at about 10 cm/s the Stephenson screen Psychrometric constant would probably be reasonable, certainly more reasonable than the ideal value used by Jeppsson which would only apply to air flows of several metres per second. In using an ideal value Jeppsson calculated saturation vapour pressures smaller than those calculated in the present study and so his vapour pressure deficits were also smaller.

To convert from vapour pressure to vapour density, as used by Jeppsson, the following conversion is needed:

$$\rho_v = (e \times 622/1013) \times 1.225 \qquad (3)$$

where ρ_v is the vapour density (g m^{-3}).

3. Method

For easy comparisons with the work of Jeppsson , the vapour density deficits calculated in this study have been categorised and presented using his statistics and format. Hourly mean VDD values are calculated separately for each of the summer months. To indicate the variability about the mean, coefficients of variation (standard deviations/mean) were calculated. These were not given by Jeppsson.

The essence of this work is to determine whether hay can be barn dried down to acceptable moisture content levels. Therefore Jeppsson has superimposed upon his VDD graphs, lines of VDD values needed to dry hay to moisture contents of 40%, 30% and 20%, which have equilibrium humidities of 90%, 84% and 75% respectively. Jeppsson used constant temperature (15°C) and pressure (1013 mb) to calculate his VDD thresholds, but in this study hourly mean values were used, to give meaningful results.

It was explained in Section 2 that Jeppsson probably used an inappropriate value for the Psychrometric constant in the VDD calculations. To allow comparison between his results and those presented in this paper which use a modified Psychrometric constant, the VDD values have been calculated using both Psychrometric constant values.

4. Results

The results of Jeppsson for Uppsala in Sweden are shown in Figure 2. The sites used for the UK analysis are shown in Figure 3, and the associated results are shown in Figure 4–10. The right columns of these figures are for the method of Jeppsson, whilst the left columns are the results using the modified psychrometric constant. The coefficients of variation are in Table 1. The maximum coefficient of variation roughly occurs at maximum VDD, and the minimum coefficient at minimum VDD.

The dome shaped curves in Figure 2 and Figures 4–10 represent the hourly fluctuation of VDD. At night when relative humidity is higher, the VDD is low, whilst during the afternoon, the heated air has a greater moisture capacity, producing the largest VDD values. In Figures 4–10 the 3 approximately straight and parallel lines represent the VDD values required for drying to a 40%, 30% and 20% moisture content.

In comparing the Swedish and UK graphs (right columns) it can be seen that the Swedish VDD curves have broader peaks than the British curves, although the actual maximum and minimum values are very similar to those from the non-coastal British stations. This difference in shape could be due to the longer hours of daylight experienced in Scandinavia than in southern Britain in summer. The graphs for Kinloss (Figure 10) are also flatter than for stations further south, once again indicating that latitude is playing a part in the broadness of the peak VDD.

TABLE 1: COEFFICIENTS OF VARIATION (MAXIMUM AND MINIMUM VALUES)

MONTH	MAY		JUNE		JULY		AUGUST		SEPTEMBER	
STATION	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX
MANSTON	0.47	0.78	0.48	0.72	0.46	0.70	0.44	0.75	0.47	0.77
BOSCOMBE DOWN	0.54	0.93	0.53	0.94	0.46	0.97	0.52	0.95	0.51	0.88
PLYMOUTH	0.62	0.88	0.64	0.85	0.58	0.83	0.61	0.88	0.55	0.82
ABERPORTH	0.67	0.88	0.66	0.91	0.60	0.85	0.63	0.91	0.55	0.76
ELMDON	0.49	0.76	0.48	0.74	0.44	0.74	0.50	0.81	0.46	0.92
LEEMING	0.49	0.70	0.46	0.75	0.44	0.62	0.50	0.76	0.42	0.85
KINLOSS	0.56	0.75	0.49	0.72	0.51	0.67	0.52	0.74	0.47	0.70

It was explained in Section 2 that if air was passed rapidly through the hay then the rapid evaporation would cause the air to cool to lower temperatures than for slow air flows, and make VDD values less. By comparing the right and left hand columns of Figure 4-10 the difference due to changing evaporation efficiency can be seen graphically. All VDD values become depressed in the right column, which means the ability of fast moving air to take up moisture from the hay is reduced, provided it has time to become saturated.

In the Swedish type of analysis, the fast air flow calculation results in a shortening of the drying period each day. This is partly compensated for by using constant temperature (15°C) in the lines of constant moisture content in Figure 2. In Figures 4-10 the VDD lines for constant relative humidity (or moisture content) vary somewhat with temperature, both during the day, and for month to month. In the summer daytime temperatures often rise above the 15°C value used by Jeppsson, which moves the constant relative humidity curves in Figures 4-10 to higher VDDs than those of Figure 2 during the daytime drying period.

All further comments will be made using the data for slow air movements in the left columns of Figures 4-10.

The Figures clearly show that position relative to the west coast of Britain is a very important factor in determining the magnitude of daytime VDDs. Figures 6 and 7 for Plymouth and Aberporth show that in 'average' summer conditions it would be very difficult to dry hay to a 20% moisture content. However, the coefficients of variation indicate that on favourable occasions hay could be dried to below 20% moisture content. In central England (Figures 5, 8 and 9) during the daytime, the average hourly humidities indicate that for all months except perhaps September, there will be a large proportion of good drying days. In late summer due to the shortening daylight hours, the hours in which drying can occur begin to get severely restricted to the early afternoon. This effect is especially noticeable in the northern stations (Figures 9 and 10).

Figure 10 for Kinloss and Figure 4 for Manston show that even though they are coastal stations, on the eastern side of the country barn drying is a viable proposition. Unlike Kinloss, Manston is not subject to so much early summer daylight and therefore at Manston May is a poorer drying month than at Kinloss.

It can be seen in Figure 1 that in humidities of greater than 90% hay dried to 20% moisture content will start to absorb moisture. When these figures are compared with those given by other authors (for example Shepherd (1957)), the hysteresis seems rather high, and so must be treated with caution. In the absence of clear advice on absorption, comments have to be brief and qualitative. Especially in the southern parts of the country, there is some evidence from the data that fans should be turned off at night and during the early morning, to avoid rewetting. In the north (Figures 9 and 10) humidity does not appear to rise so high at night as it does in the south, on average, and so rewetting would be less of a problem.

5. Conclusions

To conform with the work of Jeppsson and to carry out a fast initial study, average statistics have been used. Therefore conclusions that can be drawn are rather limited. There are good indications that in east and central parts of the UK, summer humidities are low enough for barn drying of hay from May to August to be viable. In the west, opportunities to barn dry hay sufficiently well and quickly are probably rather few.

This study has indicated that it would be worthwhile to carry out a more detailed analysis of British humidity in summer to establish the probability of getting consecutive drying days at a particular time of year and at a particular location. Relationships with wind direction may also be possible.

6. References

R Jeppsson 1979 Barn drying: Weather statistics and the use of fans - Swedish Institute of Agricultural Engineering (Uppsala).

W Shepherd 1957 Moisture relations of hay species - Australian Journal of Agricultural Research Volume 9 pp 437-445.

Any comments on this paper should be made directly to the author.

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February 1984

Figure Legends.

1. A graph showing the relationship between relative humidity and the equilibrium moisture content of hay.

2. Graphs showing the average mixing ratio deficits as a function of time of day for Uppsala in Sweden, together with baselines for the non-utilisable parts of the air's mixing ratio deficit, at three hay moisture contents.

3. Map of stations in the UK at which mixing ratio deficits have been calculated.

4. Average mixing ratio deficits as a function of time of day for Manston in the summer months, with baselines for the non-utilisable parts of the air's mixing ratio deficits, at three hay moisture contents.

5. Average mixing ratio deficits at Boscombe Down.

6. Average mixing ratio deficits at Plymouth.

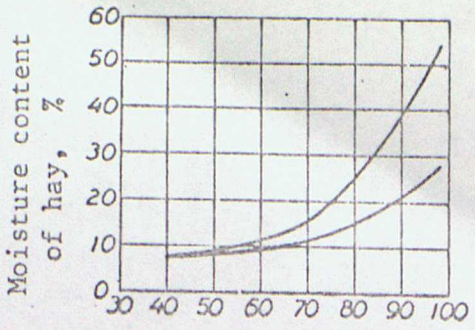
7. Average mixing ratio deficits at Aberporth.

8. Average mixing ratio deficits at Elmdon.

9. Average mixing ratio deficits at Leeming.

10. Average mixing ratio deficits at Kinloss.

FIGURE 1

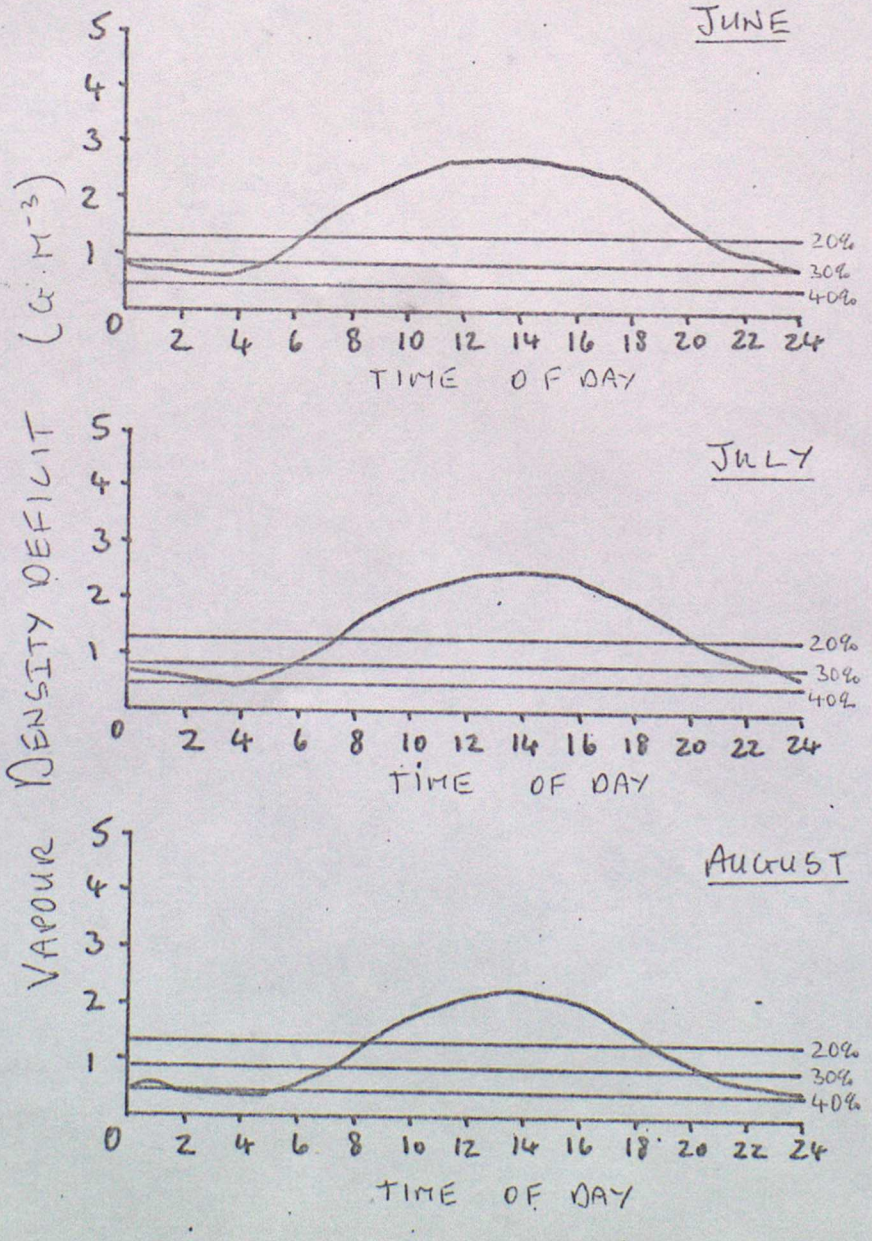


During drying (desorption)

During re-wetting (adsorption)

UPPSALA, SWEDEN

FIGURE 2.



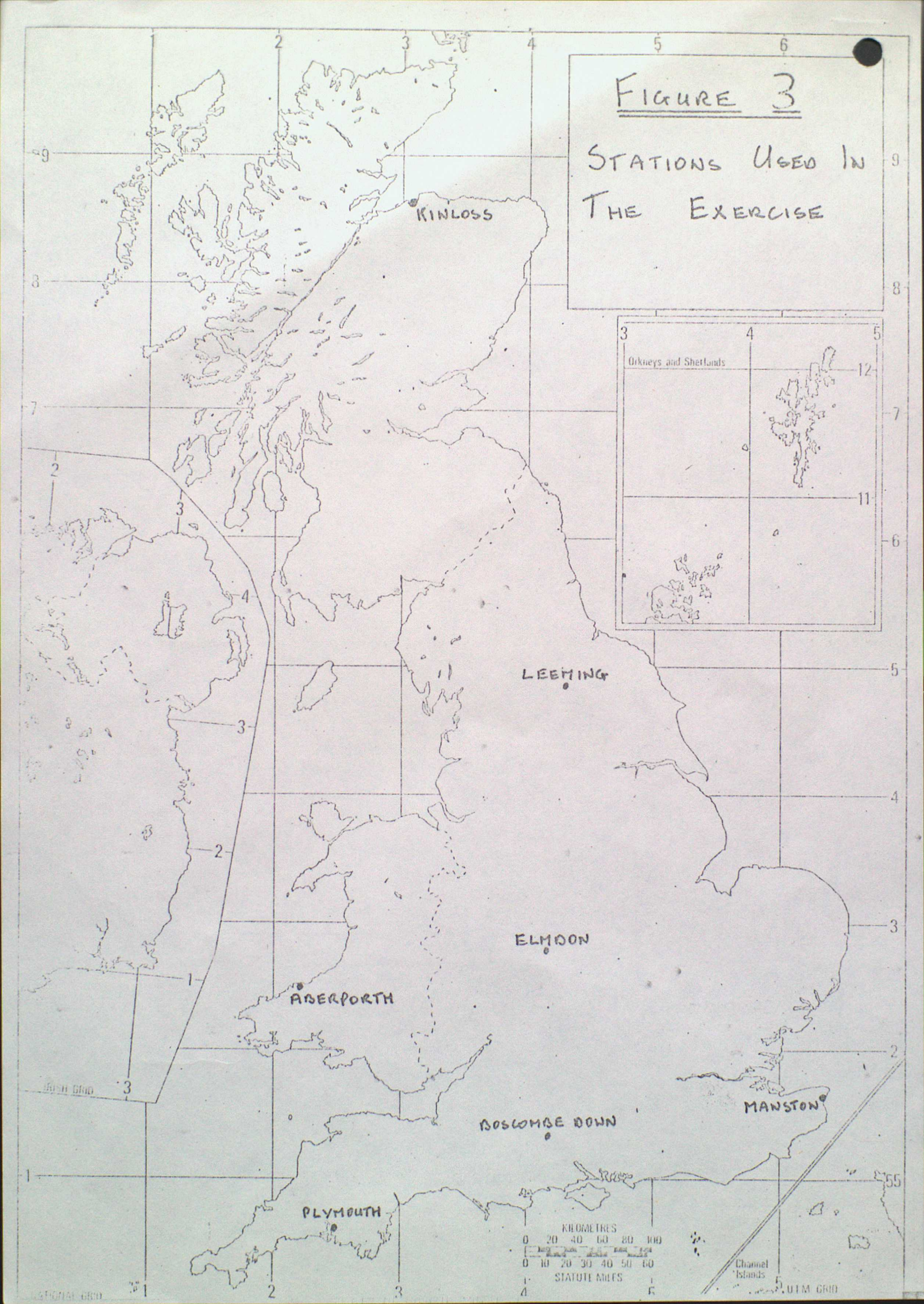
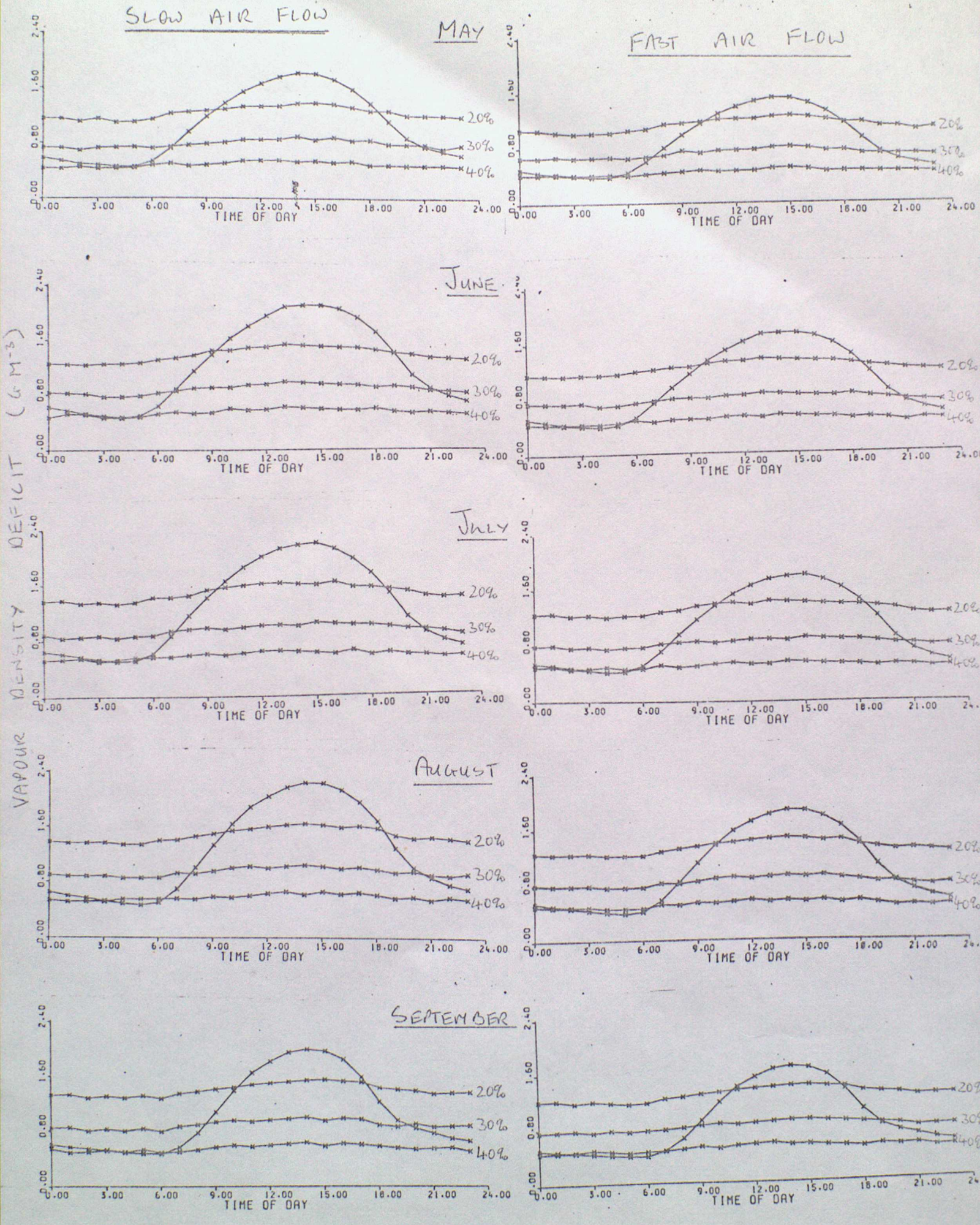


FIGURE 3
STATIONS USED IN THE EXERCISE
KINLOSS
LEEMING
ELMDON
ABERPORTH
BOSCOMBE DOWN
MANSTON
PLYMOUTH
Orkneys and Shetlands
KILOMETRES
0 20 40 60 80 100
0 10 20 30 40 50 60
STATUTE MILES
Channel Islands
NATIONAL GRID
UTM GRID

MANSTON

FIGURE 4



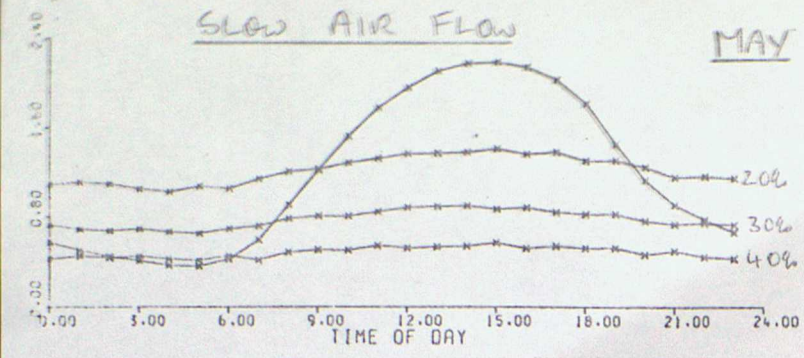
BOSCOMBE DOWN

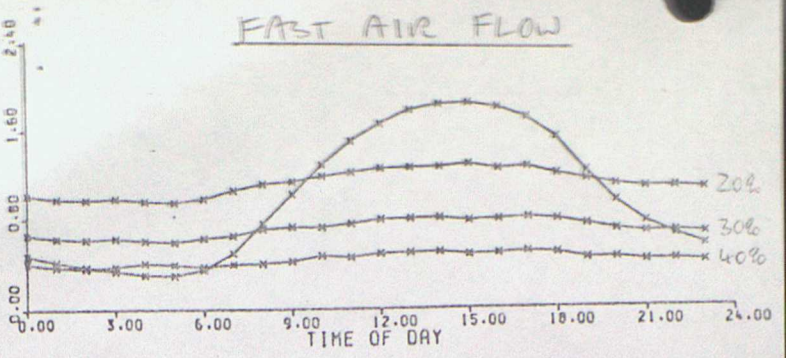
FIGURE 6

SLOW AIR FLOW

FAST AIR FLOW

MAY





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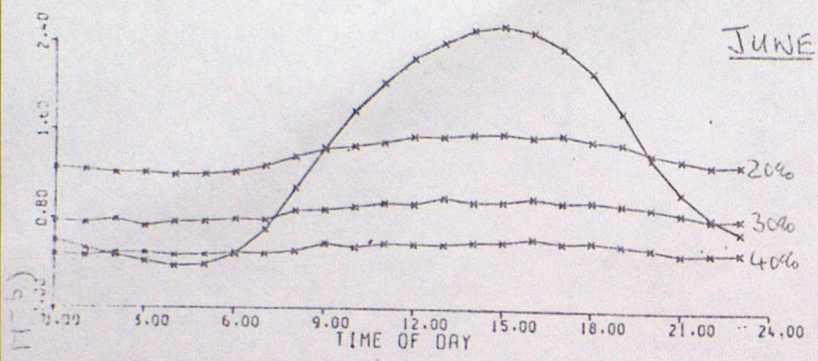
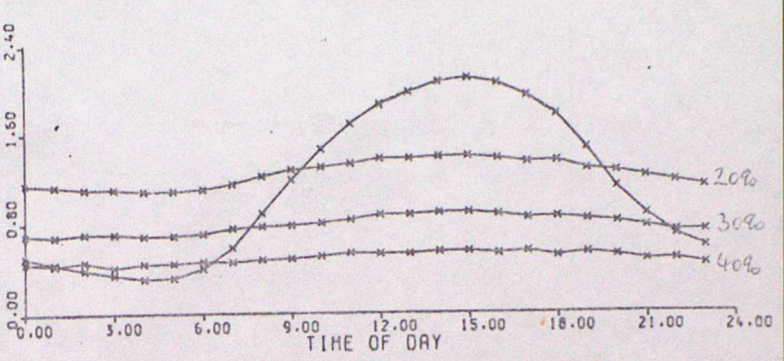
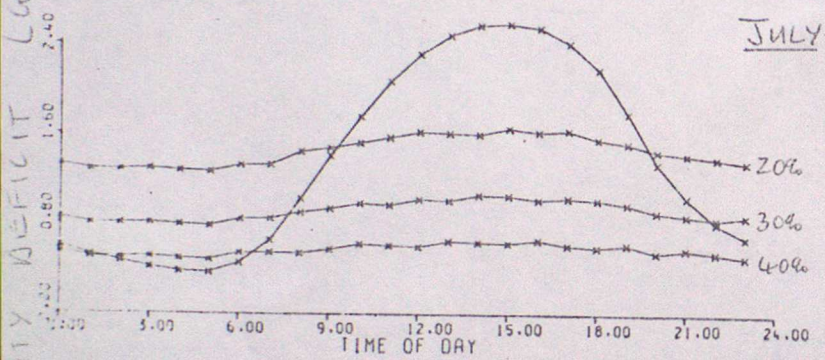
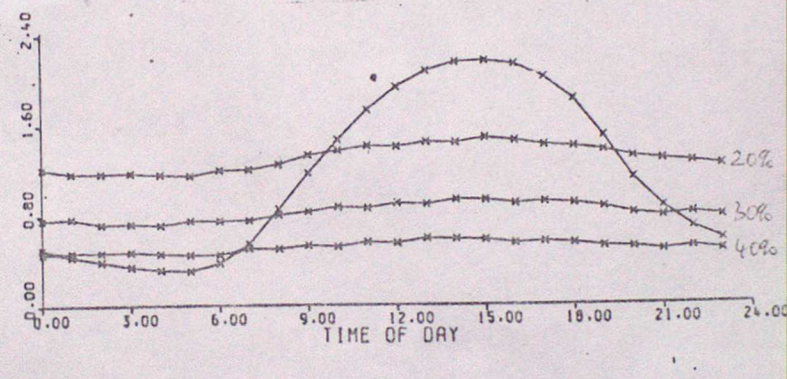




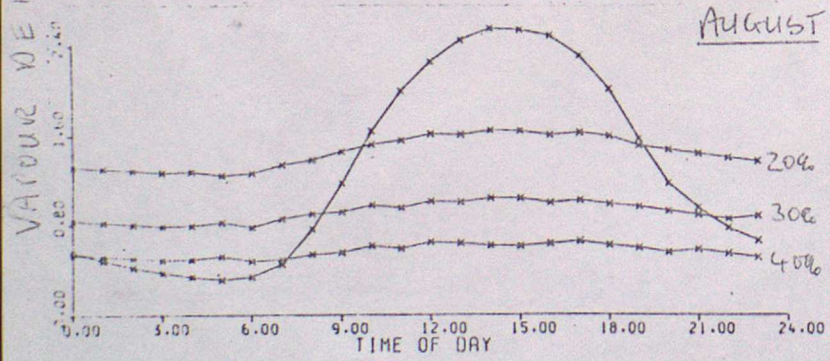
JULY

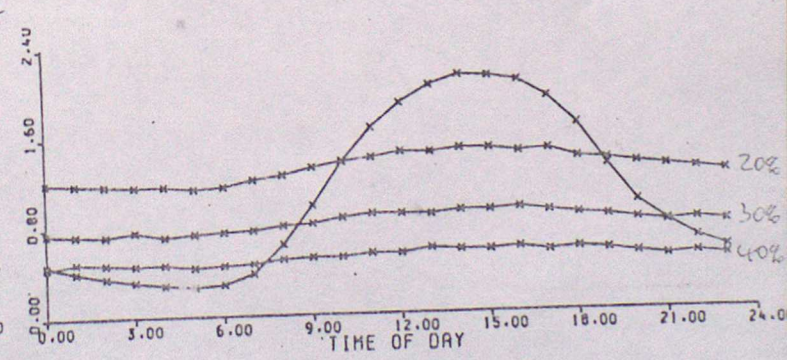




VAPOUR DENSITY DEFICIT (GM M⁻³)

AUGUST





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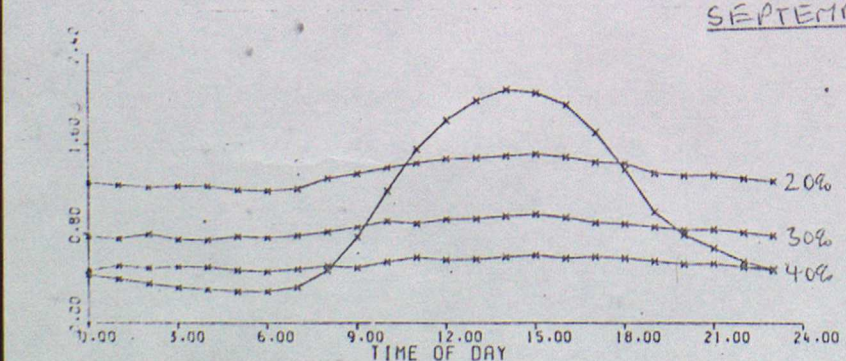
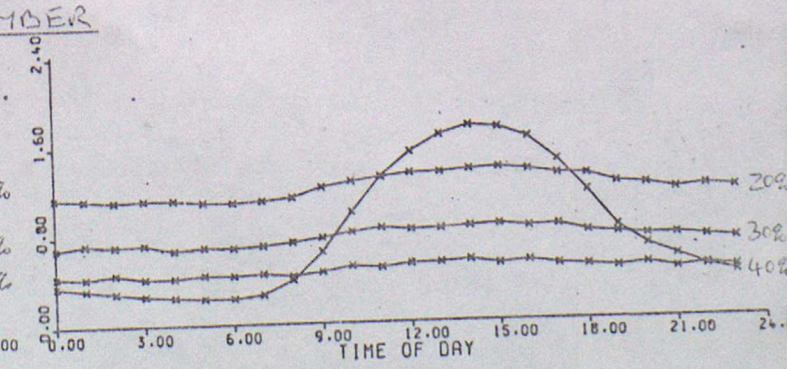




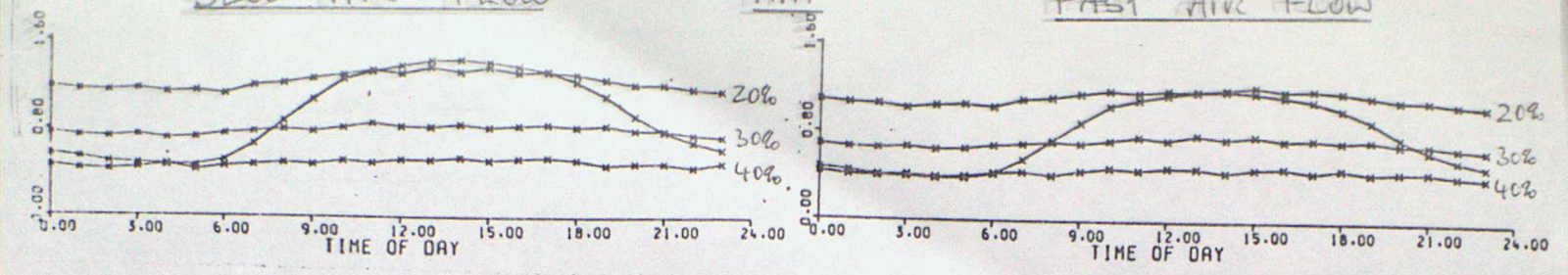
PLYMOUTH

FIGURE 6

SLOW AIR FLOW

MAY

FAST AIR FLOW



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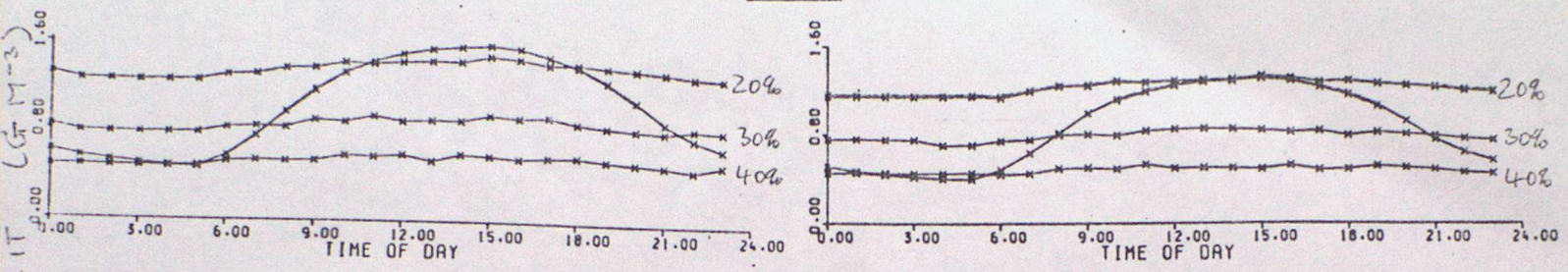

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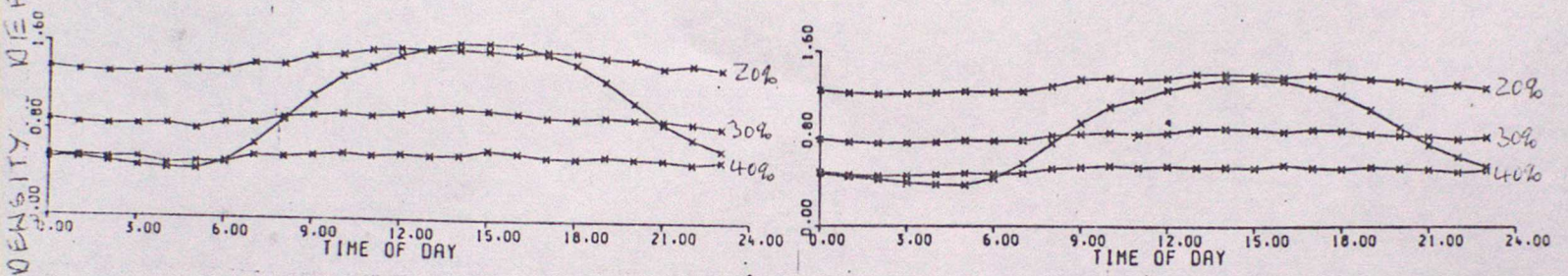

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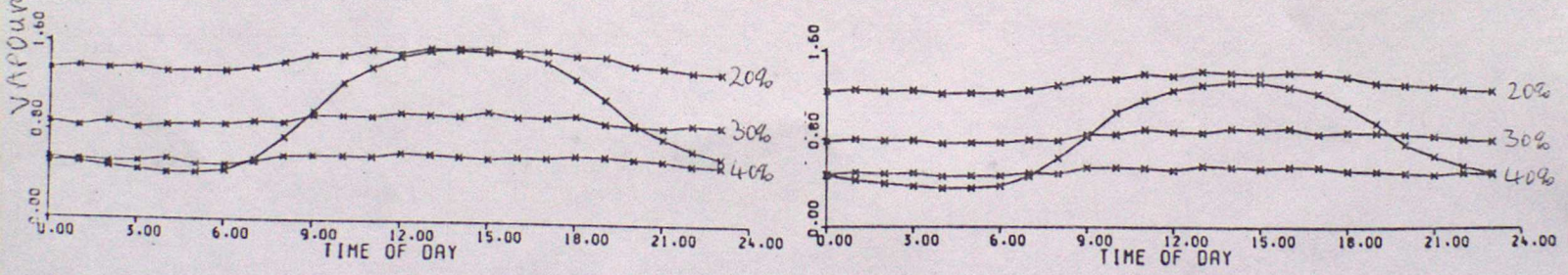

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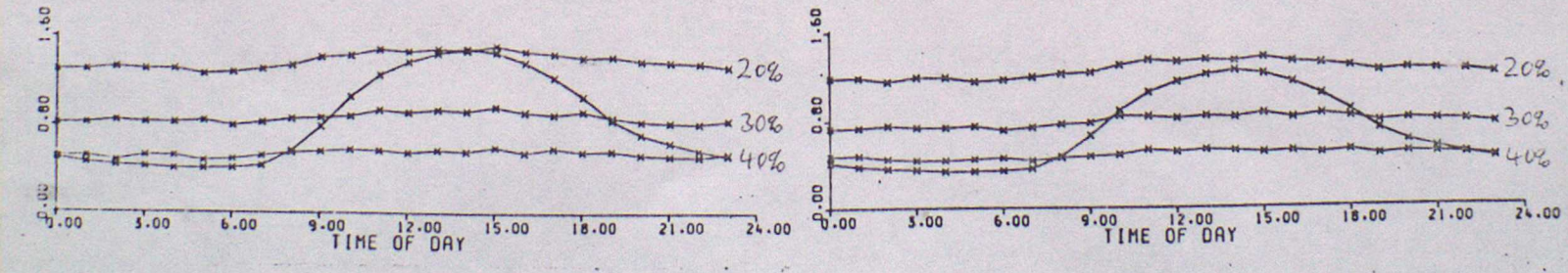


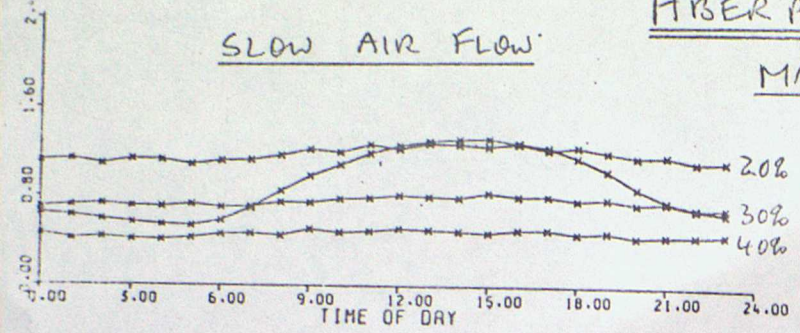
ABERPORTH

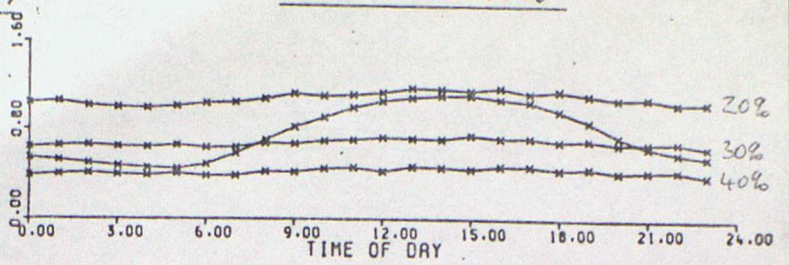
FIGURE 7

SLOW AIR FLOW

FAST AIR FLOW

MAY





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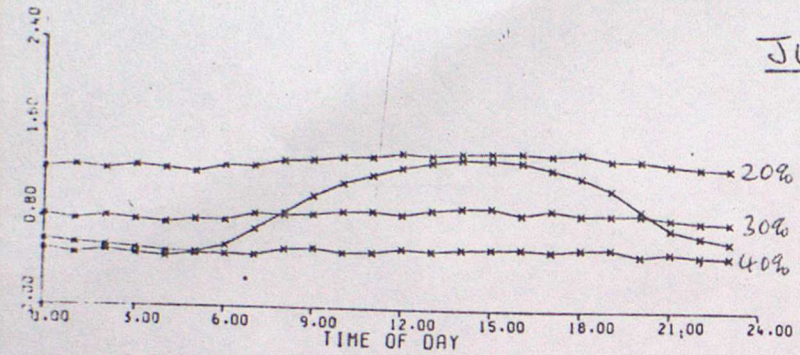

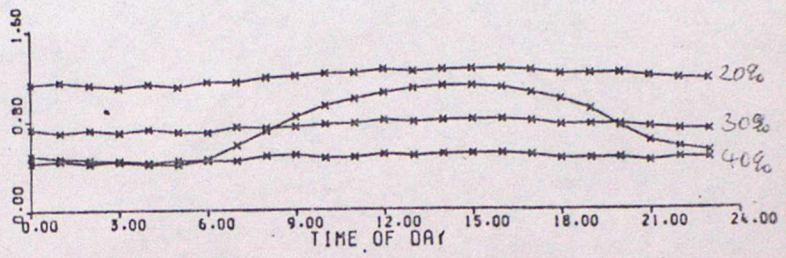

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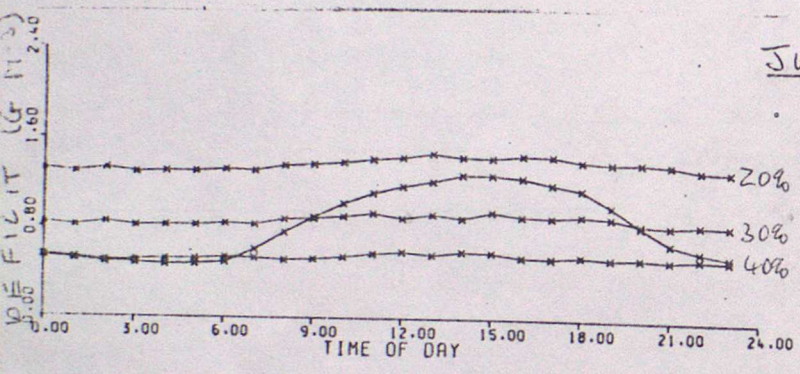

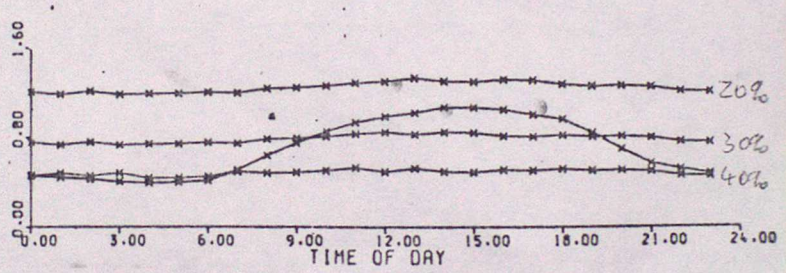

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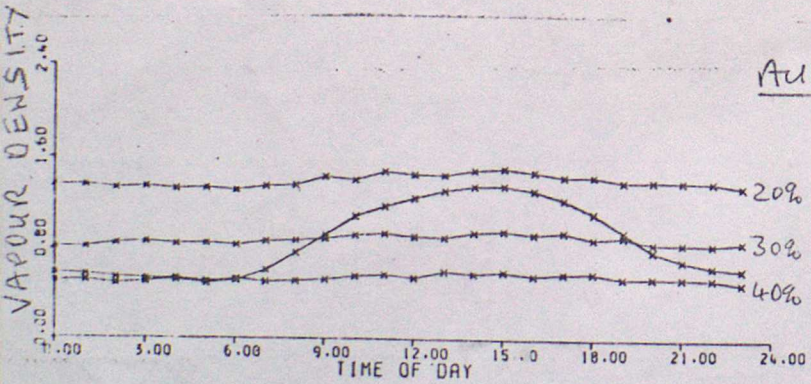

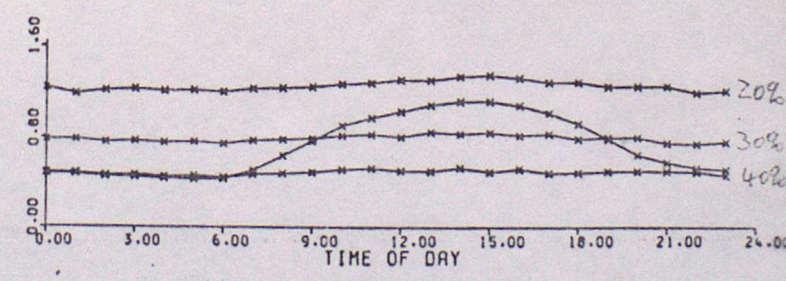

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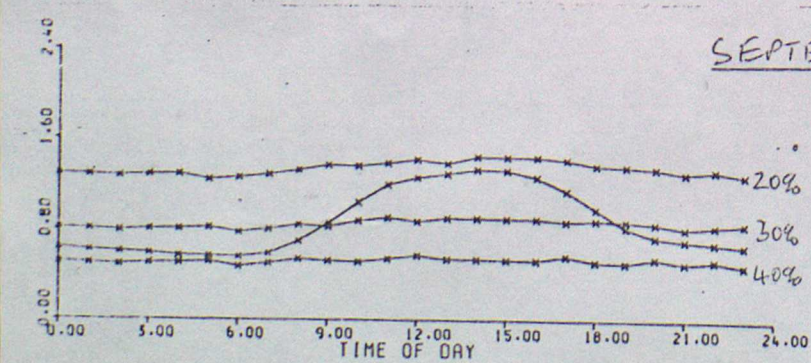
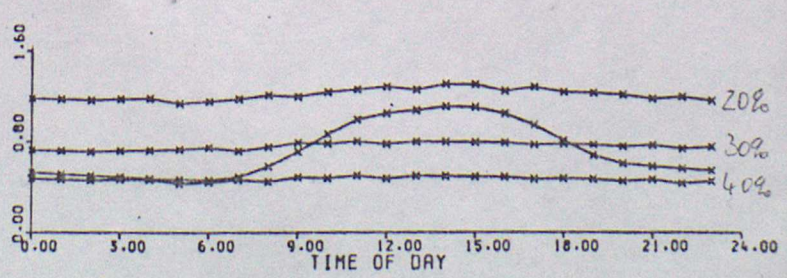


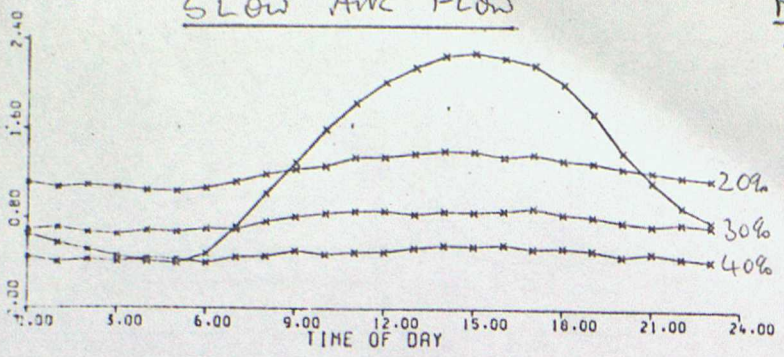


ELMDON.

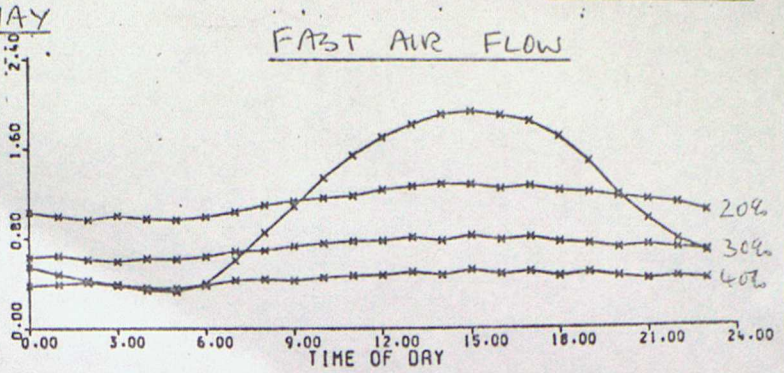
FIGURE 8

MAY

SLOW AIR FLOW



FAST AIR FLOW



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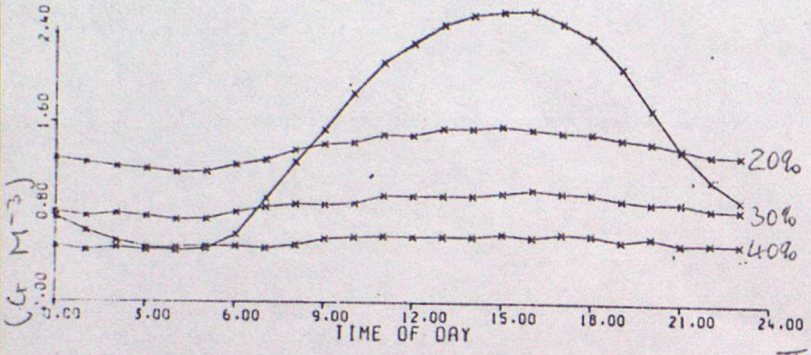

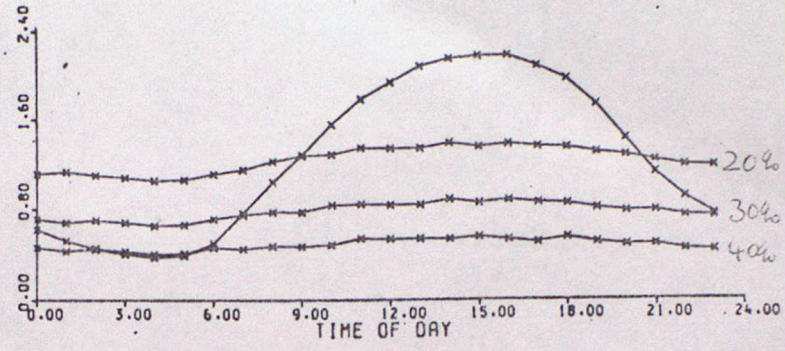

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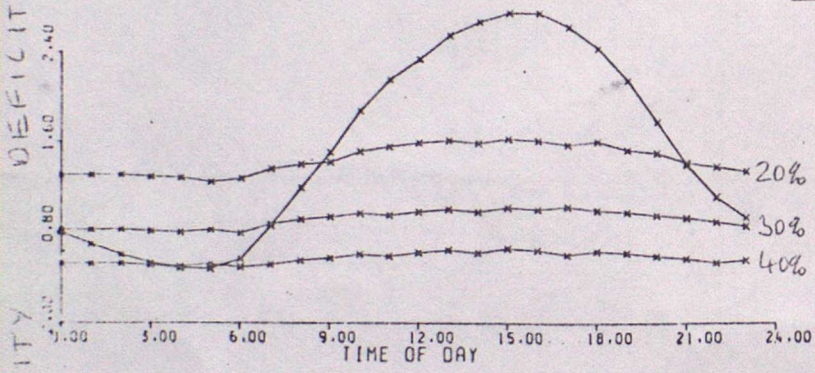

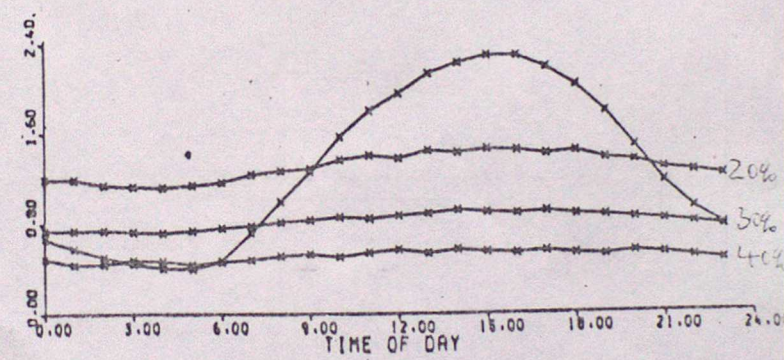

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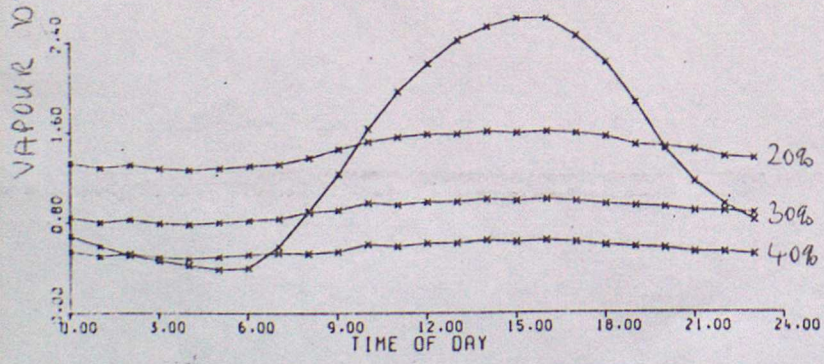

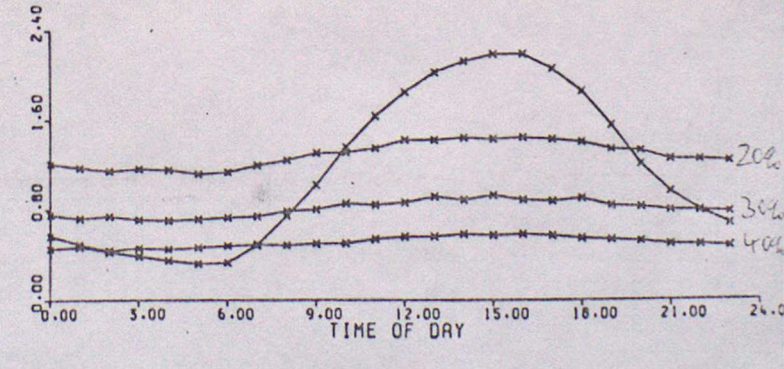

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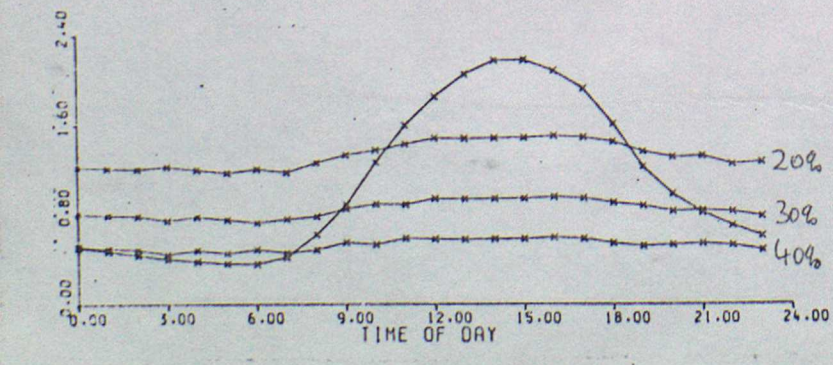
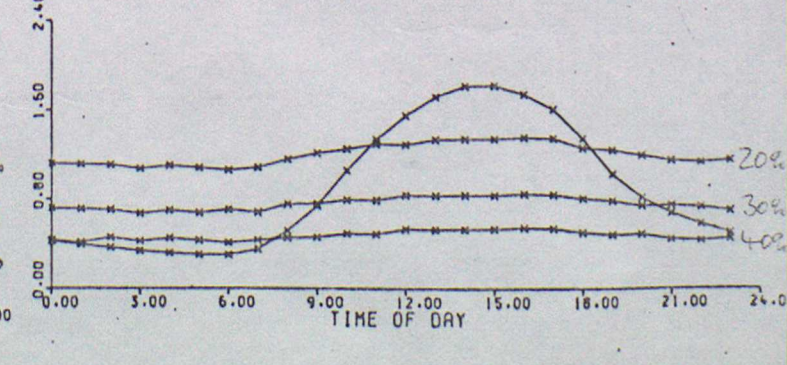


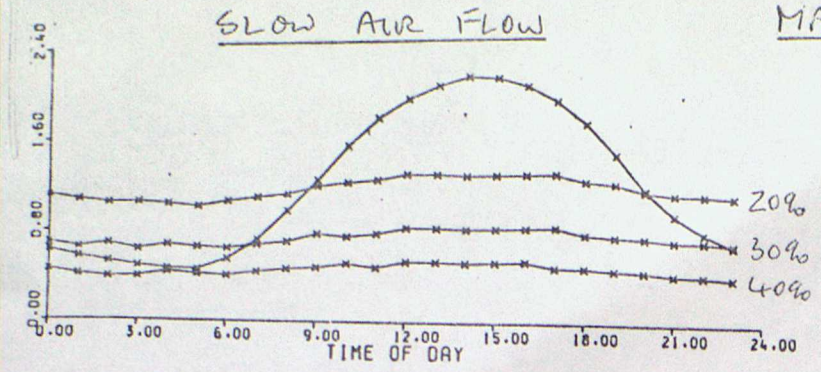


LEEMING

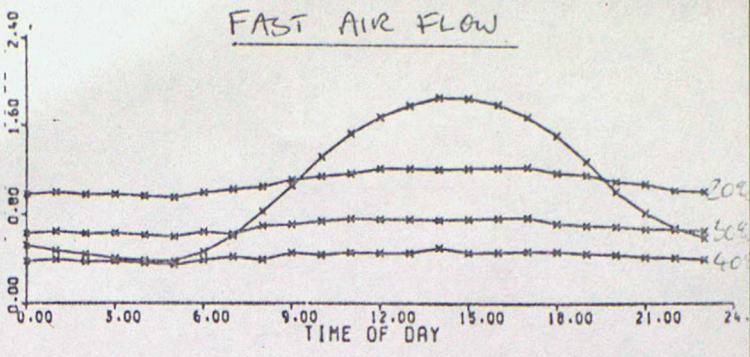
FIGURE 9

SLOW AIR FLOW

MAY



FAST AIR FLOW



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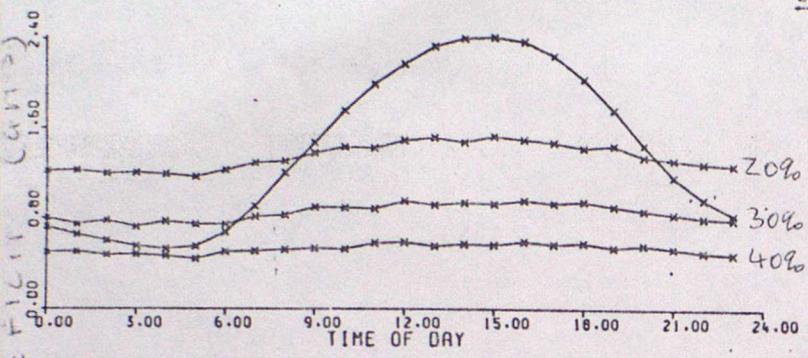

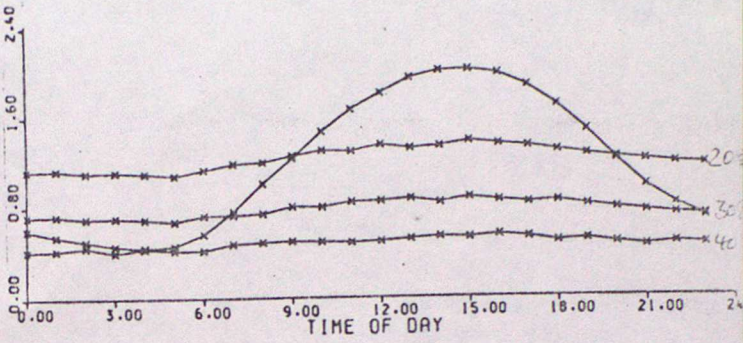

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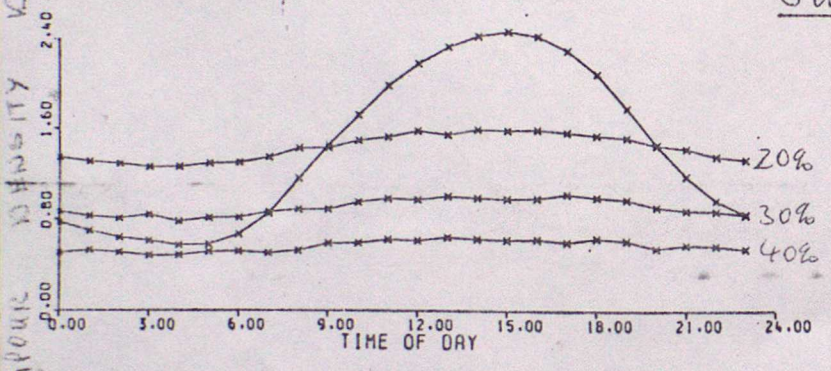

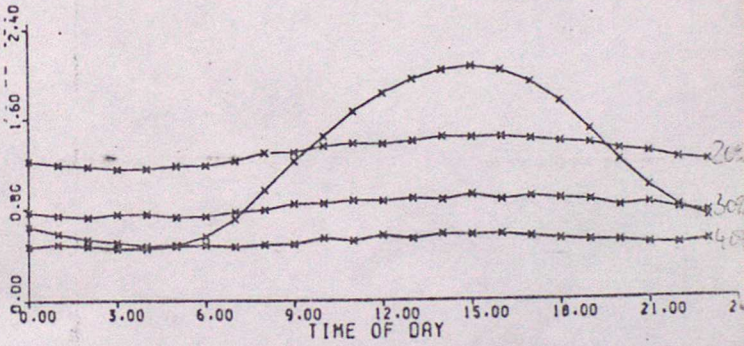

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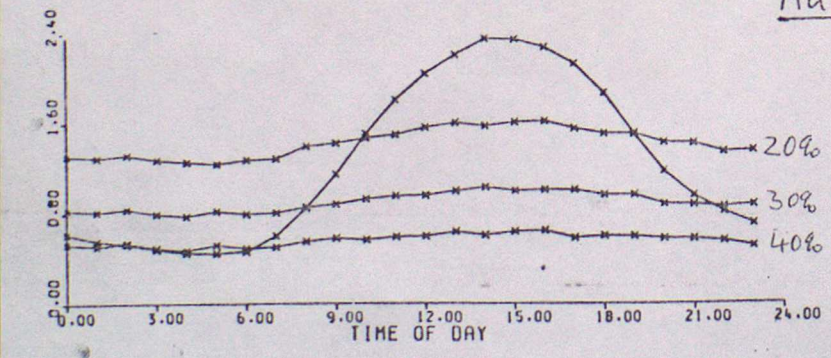

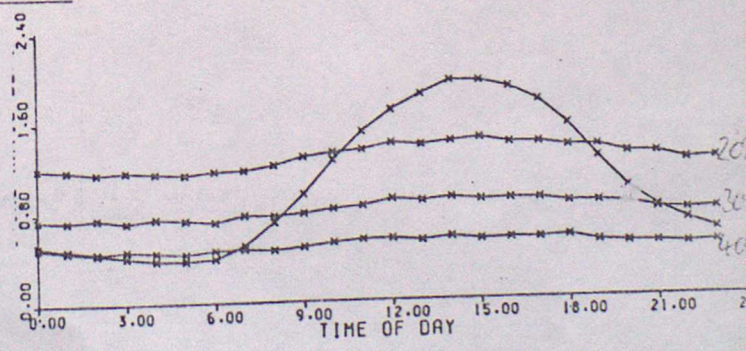

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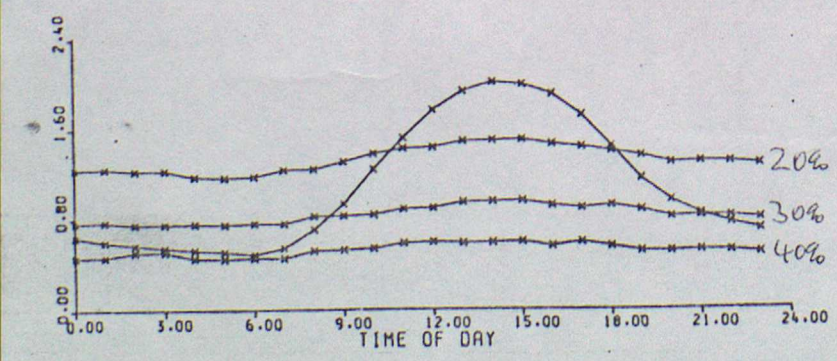
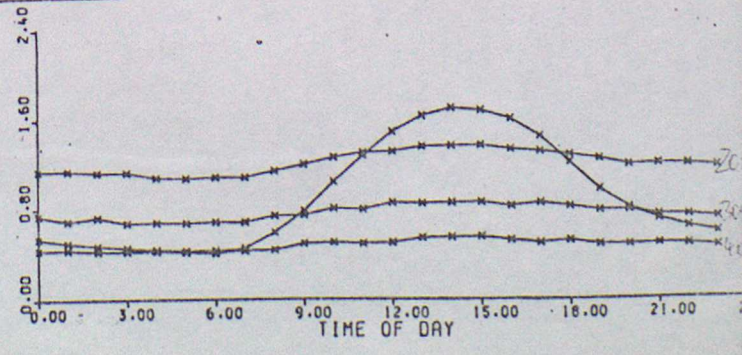




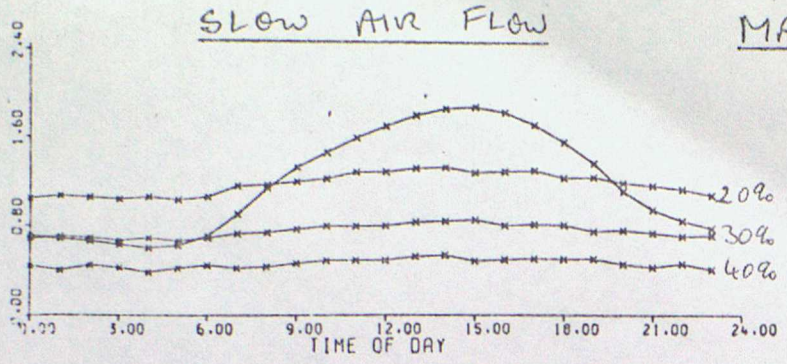
KINLOSS

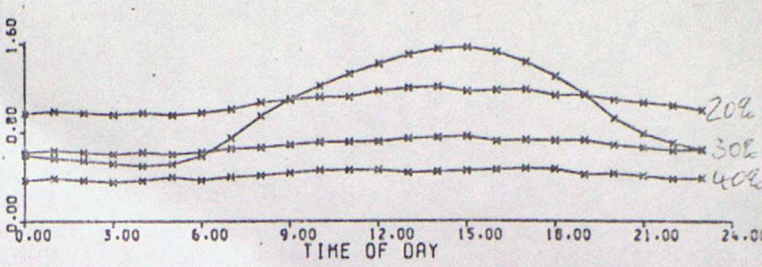
FIGURE 10

SLOW AIR FLOW

MAY

FAST AIR FLOW





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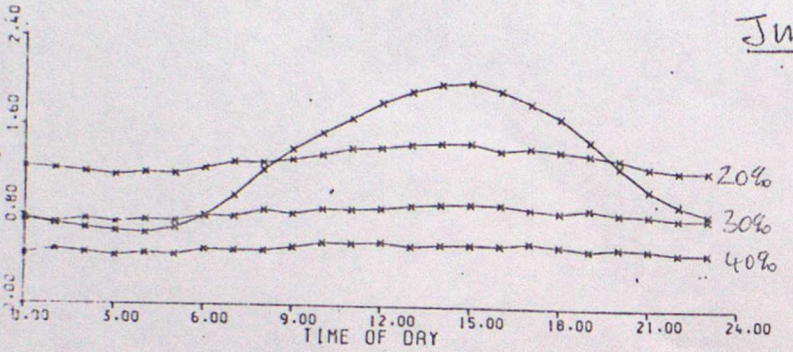
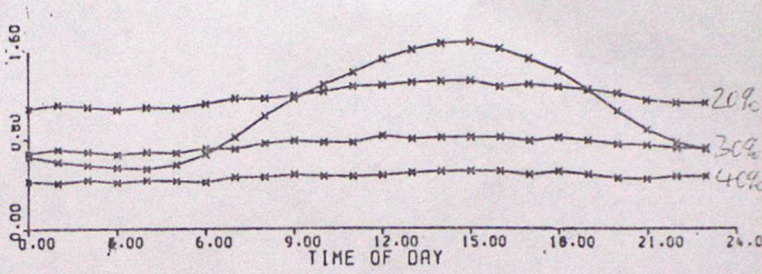
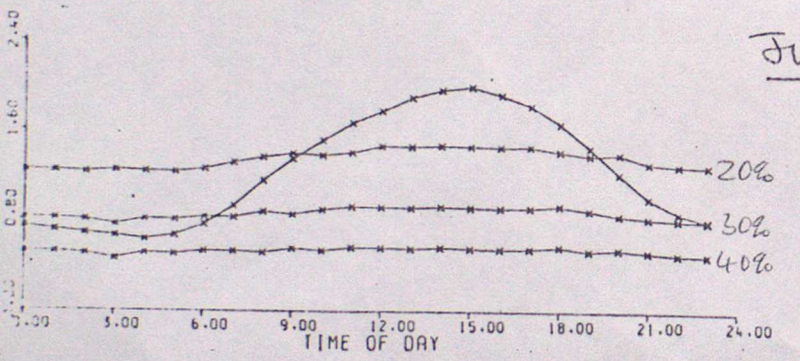
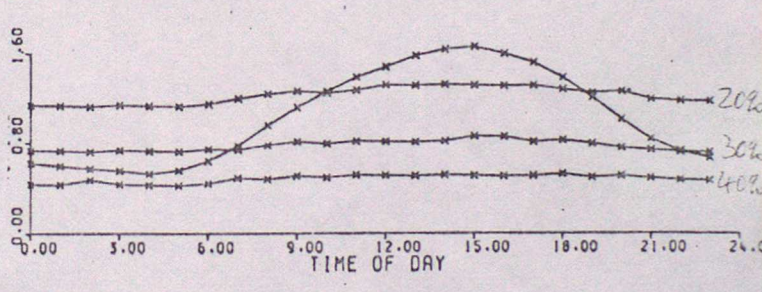




VAPOUR DENSITY DEFICIT (GR FT-3)

JULY





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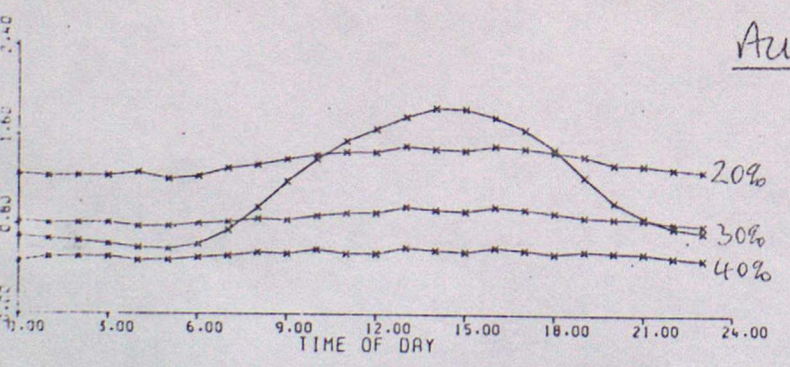

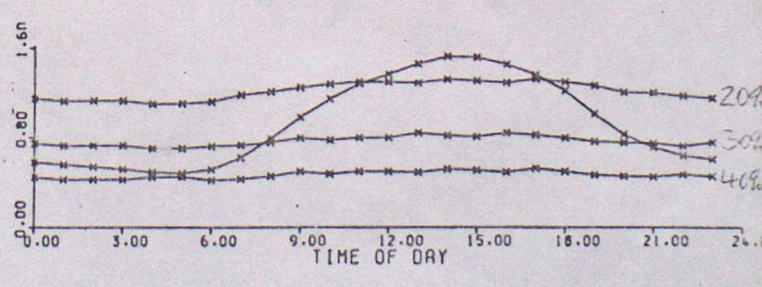

SEPTEMBER